CRATERING RATES IN THE JOVIAN SYSTEM. K. Zahnle[1], P. Schenk[2], L. Dones[3] and H. Levison[3] [1]NASA Ames Research Center (MS 245-3 Moffett Field CA 94035), [2]LPI, [3]SWRI.

We use several independent constraints on the number of ecliptic comets to estimate impact cratering rates on the Jupiter moons. The impact rate on Jupiter by 1.5-km diameter ecliptic comets is currently $\dot{N}(d>1.5\mathrm{km}) = 0.005^{+0.006}_{-0.003}$ per annum [1]. Asteroids and long period comets are currently unimportant. The size-number distribution of ecliptic comets smaller than 20 km is inferred from size-number distributions of impact craters on Europa, Ganymede, and Triton. For comets bigger than 50 km we use the size-number distribution of Kuiper Belt Objects.

Figure 1 gives the overview of the impact rate at Jupiter in general and at Europa in particular [1]. These impact rates imply cratering rates on Europa of 0.5 per Ma per 10^6 km^2 for impact craters bigger than 1 km, and of 0.015 per Ma per 10^6 km^2 for impact craters bigger than 20 km. The latter corresponds to an average recurrence time of 2.2 Ma for 20 km craters. The best current estimates for the number of 20 km craters on Europa appear to range between about twelve to thirty. This implies that the average age of Europa's surface is between 30 and 70 Ma. The average density of craters with diameter greater than 1 km on well-mapped swaths on Europa is 30 per 10^6 km^2. The corresponding nominal surface age would be 60 Ma. These two estimates are not truly independent because we have used size-number distribution of the Europan craters to help generate the size-number distribution of comets. The uncertainty of the best estimate—call it 42 Ma for specificity—is at least a factor of 3.

Discussion: By placing a heavy weight on the historical record of close encounters with Jupiter we favor generally high impact rates, especially for comets larger than a few km diameter. But we also conclude that comets smaller than a km or so are relatively rare at Jupiter, and hence that small primary craters (smaller than 10 km or so) are produced less frequently than one might expect.

Among the questions addressed by our study, the depletion of small comets and whether this depletion is characteristic of the Kuiper Belt source seems most worth additional discussion.

The Kuiper Belt size-number distribution allows us to exploit the observed number of Centaurs as a constraint on the number of ecliptic comets, provided that are free to interpolate the slope between 20 and 50 km. It is an imperfect solution because the source of the ecliptic comets—the "scattered disk"—is a dynamical subset of the Kuiper Belt as more generally defined, and because the size-number distribution of Kuiper Belt objects smaller than 50 km is currently at the edge of knowledge. Indeed, the authors of the deepest survey to date have suggested that the size-number distribution in the Kuiper Belt turns over for objects smaller than 50 km [2] (their best fitting curve is shown on Fig 1). The slope of the deduced size-number distribution seems to be in conflict with that set by the Ganymedean craters, but it is premature to draw any conclusions as of yet—observational astronomy has a long history of underestimating what has not yet been seen.

At the other end of the size spectrum, sub-kilometer comets are going missing at Jupiter. This parallels the depletion of small comets seen in the historical record of comet discovery in the inner solar system [3]. Missing sub-km comets in the inner solar system could be explained by their absence in the Kuiper Belt, by disintegration (true loss), or by extinction (becoming asteroids). Missing craters on Europa and Ganymede show that extinction is relatively unimportant. The existential question is harder to address. Abundant small craters on Triton imply that at Neptune the comets may be a collisional population rich in small bodies, but it is unclear whether the craters on Triton are of heliocentric (i.e. intruders from outside the Neptune system) or planetocentric (internal to the Neptune system, perhaps generated by a moon's disruption) origin.

There is an older view that the Kuiper Belt must have been collisionally evolved at its current location. The argument presumes that Pluto and Quaoar etc. were formed where they are now. Given this presumption, it can be shown that disk surface densities two or three orders of magnitude higher than they are now are needed to make worlds as big as Pluto and Quaoar in a reasonable amount of time [4]. Such a thick swarm of bodies inevitably generates a lot of debris. If thereafter the Kuiper Belt evolved in a way that preserved the size-number distribution, small KBOs would now be abundant. If all the ifs are granted—if we accept formation of large bodies in place, no preferential loss of small bodies, and if the classical Kuiper Belt is the source of ecliptic comets—then the absence of small comets at Jupiter poses a problem. To solve this problem would then require that most small comets vanish before they reach Jupiter, and perhaps even before they reach Neptune. Near Jupiter one might ask whether CO2 or NH3 vaporization could be disruptive; at greater distances one might ask the same of CO, N2, or CH4. Comets are known to contain volatiles that can erupt beyond Saturn. Chiron is known to have been active at 13 AU and P/Halley had an outburst at 14 AU.

A second possibility is that in the course of losing the greater part of its primordial mass the Kuiper Belt shed its smaller comets preferentially. How this might have happened is open to speculation, but the presence of gas would seem the most hopeful option. Perhaps smaller fragments were carried off with the gas, or spiralled into the inner solar system because of gas drag, leaving only the larger bodies in place. Given that more than 99% of the big objects are also lost if Pluto formed *in situ,* a bit of mass fractionation is not unreasonable.

A third choice (not necessarily inconsistent with the second) is to suggest that the larger bodies in the Kuiper Belt formed nearer the Sun, in rough analogy to how Neptune and Uranus may have formed in the vicinity of Jupiter and Saturn, only later to be scattered to greater distances [5,6]. Such a model directly accounts for the low mass of the Kuiper Belt and the rarity of Pluto-class objects [6]. Migration obviates the need for *in situ* collisional evolution in the Kuiper Belt, and so no large population of small comets need form at the Kuiper Belt's distance in the first place. The model is therefore agnostic with respect to small comets. We note that, in this model, whether a planetesimal joins the classical cold Kuiper Belt or the dynamically hot scattered disk becomes a matter of chance rather than a fate strongly tied to place of origin.

REFERENCES

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Figure caption. Data points refer to various estimates of the impact rate at Jupiter, with the exception of the Centaurs, which scales from the impact rate at Saturn [1]. Generous error bars are reminders that uncertainties are large. The labeled intermittent curves give the slopes of the size-frequency distributions as obtained from craters on Europa and Ganymede, and from the observed populations of Kuiper Belt objects (plotted through the Centaurs). The curve labeled "Bernstein et al" [2] gives a different observational account of the Kuiper Belt size distribution. Also shown are current impact rates on Jupiter by Trojan asteroids and nearly isotropic comets (NICs; these include Halley-type comets and Long Period comets). The "Trojans" is a lower limit because it considers only dynamical loss from the L4 and L5 swarms; if collisional losses are important the impact rate at Jupiter is increased proportionately.